Hearing-Preserving Approaches to the Internal Auditory Canal: Feasibility Assessment from the Perspective of an Endoscope

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■ OBJECTIVE: **Minimally invasive transcanal transpromontorial endoscopic approaches to the internal auditory canal sacrifice the cochlea. Two hearing-preserving approaches, the exclusively endoscopic transcanal infracochlear approach and the endoscope-assisted transmastoid retrolabyrinthine approach, have been controversially discussed in the literature. In this study, we examine the feasibility of these 2 approaches by means of three-dimensional surface models, a population-based analysis of the available surgical space, and dissections in human whole-head specimens.**

■ METHODS: **We reconstructed three-dimensional surface models based on clinical high-resolution computed tomography scans of 53 adult temporal bones. For both approaches, we measured the maximal extensions and the area of the surgical access windows located between landmarks on the surrounding anatomic structures. We then identified the limiting extensions and derived the cumulative distribution to describe the available surgical space. Dissections were performed to validate the corridors and landmark selection.**

■ RESULTS: **The limiting extension for the infrachochlear approach is 7.0 ± 2.7 mm from the round window to the dome of the jugular bulb. The limiting extension for the retrolabyrinthine approach is 6.4 ± 1.5 mm from the dura of the posterior fossa to the facial nerve. The cumulative distribution shows that 80% of the cohort have access window extensions ≥3 mm for both approaches.**

■ CONCLUSIONS: **This study shows that in a high percentage of the measured cohort, the access windows are sufficiently large for endoscopic approaches to the internal auditory canal. With appropriate instrumentation, these hearing-preserving minimally invasive approaches may evolve into alternatives to surgical treatment.**

INTRODUCTION

The internal auditory canal (IAC) is frequently affected by slow-growing benign tumors such as vestibular schwannomas, meningiomas, or, rarely, facial schwannomas.[1-3] These tumors can cause a deterioration of inner ear functions, leading to hearing loss, loss of balance, and vertigo.[4,5] Often, surgical treatment is indicated to prevent the evolution of tumor growth—related symptoms over time.[6,7]

The location of the IAC deep in the lateral skull base complicates surgical access. Therefore, traditional microscopic approaches such as the middle cranial fossa approach, the retrosigmoid approach, or the translabyrinthine approach (Figure 1A) are considered highly invasive and are associated with

Key words
- Endoscopic ear surgery
- Internal auditory canal
- Lateral skull base surgery
- Minimally invasive surgery
- Vestibular schwannoma

Abbreviations and Acronyms

3D: Three-dimensional
CT: Computed tomography
FN: Facial nerve
IAC: Internal auditory canal
ICA: Internal carotid artery
JB: Jugular bulb
pCFD: posterior cranial fossa dura
pSCC: posterior semicircular canal
SRS: Stereotactic radiosurgery

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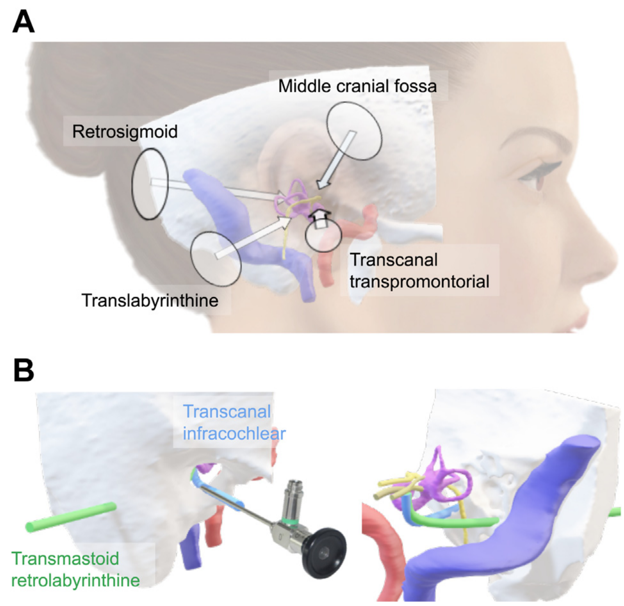

Figure 1. (**A**) State-of-the-art approaches to the internal auditory canal. (**B**) The transcanal infrachochlear approach (*light blue*) and the transmastoid retrolabyrinthine approach (*green*). Also shown: sigmoid sinus (*deep blue*), internal carotid artery (*red*), bony labyrinth (*purple*), and cranial nerves VII and VIII (*yellow*). Medical Imagery Studios, 2626 N. Lakeview, #3911 Chicago, Illinois 60614, USA.

increased operative morbidity.[8,9] With technical progress in recent years, endoscopic and endoscope-assisted transcanal approaches have become a valuable minimally invasive surgical option.[10] However, the commonly applied direct access through the promontory sacrifices the cochlea,[11-14] which limits the indication for transcanal approaches and establishes the preservation of hearing as a key challenge regarding functional outcome. In this context, we in addition identify the usefulness of minimally invasive surgical approaches compared with stereotactic radiosurgery (SRS). Recent long-term follow-up studies have shown a decrease of hearing function over time after SRS.[15] This factor may be less relevant in older patients or patients with hearing loss at diagnosis. However, in young and well-hearing patients, the surgical removal of limited vestibular schwannomas may be beneficial regarding the long-term results, especially if feasible minimally invasively.

Two alternative approaches, the exclusively endoscopic transcanal infracochlear approach[16] and the endoscope-assisted transmastoid retrolabyrinthine approach,[17-19] have been proposed to preserve the middle and inner ear when accessing the IAC. These approaches neither require craniotomies nor sacrifice the middle or inner ear and may therefore be considered minimally invasive. However, anatomic structures including the labyrinth, the internal carotid artery (ICA), the jugular bulb (JB), and the facial nerve (FN) strongly limit the surgical corridors. Therefore, the feasibility of these approaches has been controversially discussed in the literature, and objective data are scarce.

In this work, we measure the area and the maximal extensions of the surgical access windows in three-dimensional (3D) surface models from 53 temporal bones and present a population-based analysis to evaluate the feasibility of both approaches.

METHODS

Surgical Approaches

The transcanal infracochlear approach is exclusively endoscopic.[16,20] As shown in **Figure 1B**, the corridor runs through the external auditory canal and passes inferior to the basal turn of the cochlea to reach the infracochlear region. From there, the corridor turns around the cochlea, and the IAC is accessed from below. Surgical steps include a tympanomeatal flap, a transcanal hypotympanotomy, bone removal to expose the JB inferiorly and the ICA anteriorly, exposure of the infracochlear tunnel, and thinning of the cochlear basal turn to widen the infracochlear tunnel (**Figure 2A—E**). Four structures limit the transcanal infracochlear approach: the cochlea superiorly, the ICA anteriorly, the JB inferiorly, and the FN posteriorly[20] (**Figure 2F**).

The transmastoid retrolabyrinthine approach (also referred to as the retrofacial or infralabyrinthine approach) is used in endoscope-assisted surgery.[17-19,21,22] **Figure 1B** shows that the corridor runs through the mastoid part of the temporal bone and passes the labyrinth inferiorly, between the JB and the mastoid segment of the FN. The corridor then turns around the posterior semicircular canal (pSCC) to access the IAC from below. Surgical steps include a complete mastoidectomy, exposure and skeletonization of the inferior extent of the pSCC, skeletonization of the sigmoid sinus and the JB, location and skeletonization of the mastoid segment of the FN, and drilling of the bone below the IAC (**Figure 2G—L**). The posterior cranial fossa dura (pCFD) and the sigmoid sinus may be pushed backward to gain some exposure in the more lateral parts of the mastoidectomy. Four structures limit the transmastoid retrolabyrinthine approach: the pSCC superiorly, the mastoid segment of the FN anteriorly, the JB inferiorly, and the pCFD posteriorly[23] (**Figure 2M**).

3D Temporal Bone Reconstruction and Measurement

We acquired high-resolution computed tomography (CT) scans of 53 adult temporal bones from 29 specimens with a voxel size of $0.156 \times 0.156 \times 0.2$ mm^3 (SOMATOM Definition Edge [Siemens AG, Erlangen, Germany]). For each scan, we reconstructed 3D surface models of the temporal bone, the IAC, the JB, the ICA, the FN and the labyrinth with threshold-based segmentation software (Amira [FEI, Bordeaux, France]). The proposed study was approved by our institutional review board (KEK-BE 2016-00887).

We used the following measurement procedure, taking into account anatomic landmarks, the shape of surrounding structures, and the angle of approach of the instrument, or the endoscope, respectively:

A) Definition of the structures and landmarks relevant for the approach (**Figure 3A**)

B) Alignment of the view on the 3D surface model with the direction of the surgical corridor (endoscope view) (**Figure 3B**)

C) Marking of the structures and the landmarks in endoscope view (**Figure 3C**)

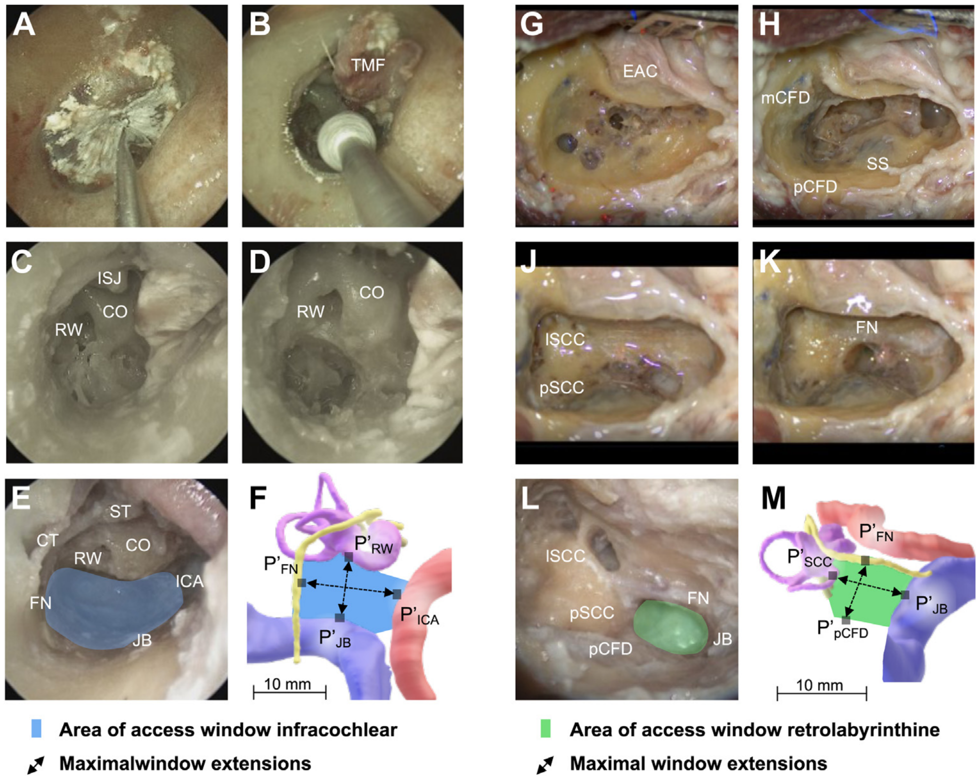

Figure 2. Surgical steps of the infracochlear (*left*) and the retrolabyrinthine approaches along with a visualization of the access windows and their appearance in dissections. (**A**) Infracochlear approach tympanomeatal flap. (**B**) Widening of the external auditory canal. (**C**) Transcanal hypotympanotomy and bone removal to expose the jugular bulb inferiorly and the internal carotid artery anteriorly. (**D**) Exposure of the infracochlear tunnel. (**E**) Thinning of the cochlear basal turn and further skeletonization of all structures to widen the infracochlear tunnel. (**F**) Representation in the three-dimensional model. (**G**) Retrolabyrinthine approach mastoidectomy. (**H**) Exposure of the posterior cranial fossa dura (pCFD) and the sigmoid sinus (SS). (**J**) Skeletonization of the inferior extent of the posterior semicircular canal (pSCC), the jugular bulb, and the mastoid segment of the facial nerve. (**K**) Drilling of the bone below the internal auditory canal and opening of the retrofacial tunnel. (**L**) View of the surgical window. (**M**) Representation in the three-dimensional model. P' denotes projected landmarks. CO, cochlea; CT, chorda tympani; EAC, external auditory canal; FN, facial nerve; ICA, internal carotid artery; ISJ, incudostapedial joint; JB, jugular bulb; mCFD, middle cranial fossa dura; RW, round window; SCC, semicircular canal; ST, stapes; TMF, tympanomeatal flap.

D) Projection of the marked points and landmarks onto a plane that is orthogonal to the surgical corridor (endoscope view plane) (Figure 3D)

E) Measurement of distances between projected landmarks (i.e., the extensions of the surgical access window), calculation of the area within projected points along structures (i.e., the area of the surgical window), and calculation of the diameter of the largest inscribed circle within the area (Figure 3E).

We manually aligned the view on the 3D surface models (B) and marked points (C) with the Amira software. We identified and highlighted landmarks in axial CT slices before marking them on the 3D surface model. Points along structures were marked on the 3D surface models only. To account for subjective rater errors, 2 independent raters performed the manual steps (B) and (C), and the average results are reported in this work. For transformations (D) and calculations (E), we used MATLAB (MathWorks Inc., Natick, Massachusetts, USA).

Landmark Selection and Measurements

We selected relevant structures and landmarks according to the structures that limit the surgical approaches (see previous section). For the transcanal infracochlear approach, we marked points along the cochlea, the ICA, the JB, and the FN, and extracted the following landmarks from the CT slices (Figure 3A):

- the center of the round window (P_{RW})
- the most posterior point of the ICA at the axial level of the bony annulus (P_{ICA})

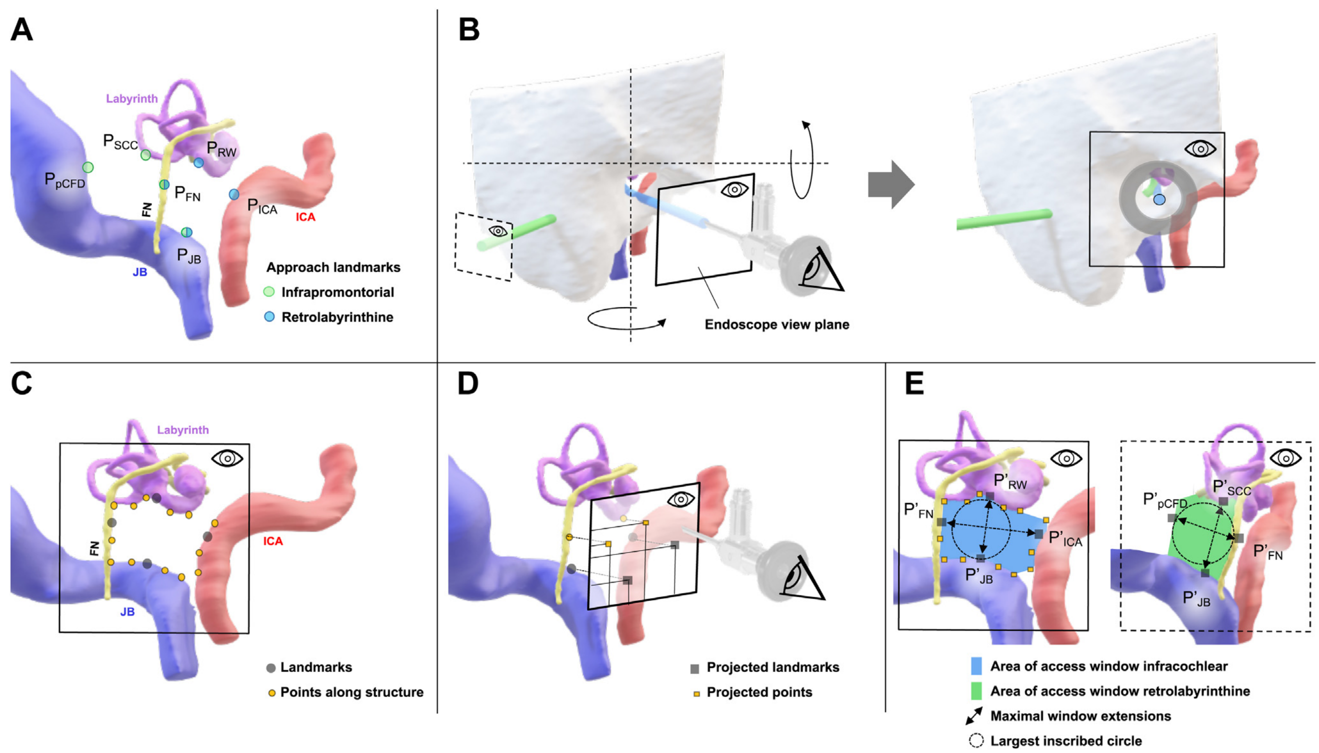

Figure 3. The measuring algorithm and landmarks for both approaches. (**A**) Landmark and structure definition. (**B**) Manual rotation to endoscopic view. (**C**) Landmark and structure marking. (**D**) Projection to endoscope view plane. (**E**) Extension and area calculation. P denotes landmarks. FN, facial nerve; ICA, internal carotid artery; JB, jugular bulb; pCFD, posterior cranial fossa dura; RW, round window; pSCC, posterior semicircular canal.

- the JB dome (i.e., the most superior point of the JB) (P_{JB})
- the FN at the axial level centered between the JB and the labyrinth (P_{FN}).

We measured the vertical extension (i.e., from superior to inferior limit) between the projected landmarks $P'_{RW} - P'_{JB}$ and the lateral extension (i.e., from posterior to anterior limit) between $P'_{FN} - P'_{ICA}$ (Figure 3E).

For the transmastoid retrolabyrinthine approach, we marked points along the pSCC, the FN, the JB, and the pCFD, and extracted the following landmarks from the CT slices (Figure 3A):

- the most inferior point of the pSCC (P_{pSCC})
- the FN at P_{FN}
- the JB dome at P_{JB}
- the pCFD at the axial and sagittal level of P_{FN} (P_{pCFD}).

We measured the vertical extension between the projected landmarks $P'_{pSCC} - P'_{JB}$ and the lateral extension between $P'_{pCFD} - P'_{FN}$ (Figure 3E).

To validate the examined landmarks associated with the 2 approaches, we performed dissections in a whole-head cadaveric specimen. After preoperative scanning, both surgical corridors were opened in the specimen until the IAC was reached. Landmarks were then identified in the specimen and visually compared with landmarks identified in the 3D surface model (Figure 2F and M). We used 0° straight and 30° angled endoscopes (2.7 mm diameter HOPKINS telescopes [Karl Storz SE & Co. KG, Tuttlingen, Germany]) and a standard otology drill system (OsseoDuo control unit, Nano micromotor and PM2 handpiece [Bien-Air Surgery SA, Le Noirmont, Switzerland]).

Limiting Surgical Access Window Extensions

Previous work has suggested that the feasibility of the approaches largely depends on the access window extensions,[18,24,25] and specific values of minimal extensions required for a successful intervention have been reported.[23] Therefore, we report the reverse cumulative distribution of the access window extensions, which acts as a measure of what proportion of our cohort showed equally large or larger extensions than a reference extension (e.g., the minimal extension required for the approach).

RESULTS

Table 1 summarizes the measured extensions and area of the surgical access windows, as well as the diameter of the inscribed circle for both approaches. Figure 4 shows the distribution of the extensions and the diameter of the inscribed circle. **Figure 5** shows the reverse cumulative distribution of the extensions and the diameter of the inscribed circle. For the infrachochlear approach, the vertical extension $P'_{RW} - P'_{JB}$ limited the approach, mainly restricted by high-riding JBs. For the retrolabyrinthine approach, the lateral extension between the pCFD and the FN $P'_{pCFD} - P'_{FN}$ limited the approach. The overall inter-rater error was 7.92% ± 7.4%. We did not find any statistically relevant differences in gender or age.

DISCUSSION

In the present study, we examined 2 hearing-preserving surgical approaches to the ICA, the fully endoscopic transcanal infrachochlear approach and the endoscope-assisted transmastoid retrolabyrinthine approach. For both approaches, we measured the extensions and the area of the surgical access windows, located between the labyrinth, the FN, the ICA, and the pCFD. In addition, we report the largest inscribed diameter and the cumulative distribution of all data showing which percentage of our cohort has extensions larger than a reference extension of interest (e.g., the minimal needed extension for the approach, or the size of an endoscope). For the infrachochlear approach, the limiting vertical extension ranges at 7.0 ± 2.7 mm and the inscribed diameter at 7.0 ± 1.8 mm. For the retrolabyrinthine approach, the limiting lateral extension ranges at 6.4 ± 1.5 mm and the inscribed diameter at 5.3 ± 1.4 mm.

The infracochlear approach has received little interest, with 1 single case with near-total cochlea preservation[26] and a limited number of cadaver studies with the aim of vestibular schwannoma resection.[16,20] The endoscope-assisted retrolabyrinthine approach has been controversially discussed in the literature. On the one hand, various groups have reported successful interventions regarding hearing preservation.[17,19,22] For example, reports of successful complete resections of small vestibular schwannomas in 8 of 10 cases[21] and 4 of 4 cases,[18] with no hearing deterioration indicate that this approach can be a safe surgical option in the treatment of small intracanalicular tumors. On the other hand, these results are put into question because of their superiority compared with results of other studies and the directed subject selection, which was based on favorable anatomy.[21]

Access window extensions and structures interfering with the surgical corridor have repeatedly been reported to be a decisive reason for the successful outcome of operations or dissections, especially for the retrolabyrinthine approach.[18,23-25] A high JB or limited space between the sigmoid sinus and pSCC were the main causes for unsuccessful interventions when the retrolabyrinthine approach was first applied in 2002.[24] More recent studies identified sufficient space between the pSCC and the JB as a key requirement for good IAC exposure when analyzing CT scans.[18,25] Comert et al.[23] achieved a straight corridor to the IAC in 73% of the cases by drilling more of the mastoid toward the digastric ridge in cadaver heads. Only when the distances FN—JB and JB—cochlea were <2.9 mm and 2.6 mm, respectively, the approach could not be performed. The reverse cumulative distribution of our results suggests that 83% of our cohort have extensions >2.9 mm and would be indicated for this approach. Approximately 90% of our cohort have inscribed circles <2.7 mm in diameter, such that the approach could be visualized with common otologic endoscopes, which are 1.9—2.7 mm in diameter.[27]

The access windows in the studies cited earlier were defined between the labyrinth, the JB, the FN, and the pCFD or the sigmoid sinus, which is in line with our study. Also, the found extensions are comparable to our results. Vertical extensions were measured as vestibule − JB (5.79 ± 2.11 mm)[23] or pSCC − JBdome (5.47 ± 3.26 mm,[28] and 4.60 ± 3.47 mm.[29]). Lateral extensions were measured as FN − pCFD (5.67 ± 1.49 mm[23]) or FN − SigmoidSinus (8.66 ± 2.71[28] and 8.40 ± 2.74[29]). Similar reference numbers are missing for the infracochlear approach. A summary of outcomes for other approaches can be found in Yacoub et al.[30]

The examined minimally invasive approaches have advantages including possible hearing preservation and less surgical morbidity compared with standard open approaches. In particular, the possibility of approaching the IAC requiring brain retraction or sacrificing the inner ear is promising. A possible drawback of both approaches is the limited exposure of the IAC, especially toward the fundus.[18,20,21,31] Although the present study does not report the exposure of the IAC, various groups using endoscopes in the retrolabyrinthine approach have found promising results in this regard. Results include that, on average, approximately 73% of the IAC could theoretically be exposed when analyzed in CT scans,[25] that the IAC could be successfully opened in 16 of 20 dissections of cadaveric temporal bones with an average exposure of 72.44% ± 14.19%,[29] and that the IAC could be fully exposed in all specimens ($n = 9$) when also exposing up to 20 mm of the retrosigmoid dura in a further recent cadaver study.[32] In the dissections, the angle of the approach with respect to the IAC presented a main difference between the 2 approaches. The retrolabyrinthine approach allowed for more exposure of the IAC and a focus on the posterior wall. In contrast, the infracochlear approach allowed better exposure of the inferior wall of the IAC. Advantageously, the infracochlear approach is less invasive, requiring less bone removal. In this context, we have to be

Table 1. Extensions and Area of the Surgical Access Window

	Infrachochlear Approach, Mean ± Standard Deviation (Range)	Retrolabyrinthine Approach, Mean ± Standard Deviation (Range)
Vertical extension (mm)	7.0 ± 2.7 (1.5—11.5)	7.5 ± 2.6 (2.0—12.4)
Lateral extension (mm)	10.8 ± 1.6 (8.4—14.9)	6.4 ± 1.5 (3.2—10.0)
Area of exposure (mm^2)	71.5 ± 27.5 (19.2—125.8)	41.7 ± 18.5 (6.4—79.4)
Diameter of inscribed circle (mm)	7.0 ± 1.8 (2.8—10.4)	5.3 ± 1.4 (2.0—8.0)

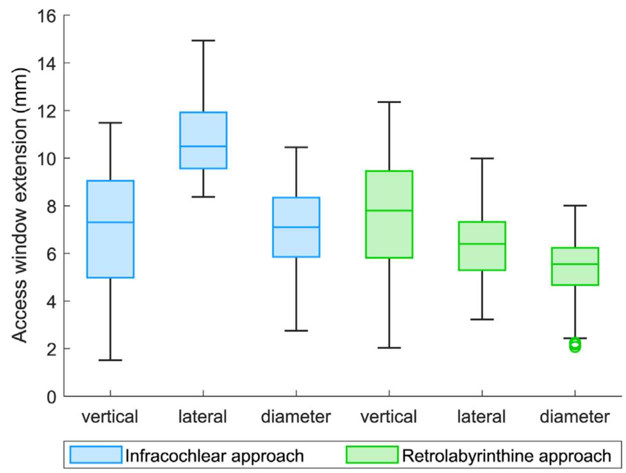

Figure 4. Distribution of the surgical access window extensions in 53 specimens.

aware that many patients eligible for minimally invasive surgery would also be eligible for SRS. In particular, elderly patients or patients presenting with unserviceable hearing would benefit from this therapeutic option. However, recent studies have shown a continuous decrease in hearing in long-term follow-up after SRS for vestibular schwannoma. Therefore, we consider multidisciplinary counseling of patients requiring a therapeutic intervention as key to the successful choice of treatment modality. The indication for a specific approach largely depends on

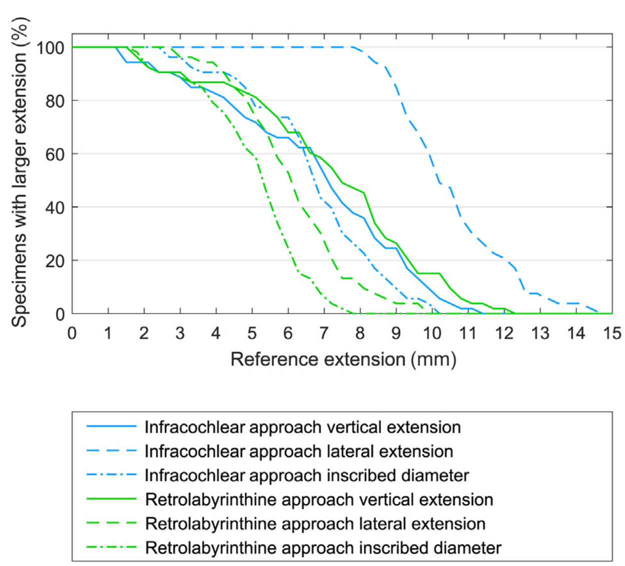

Figure 5. Reverse cumulative distribution of the surgical access window extensions in 53 specimens. The curves show the proportion of specimens with larger window extensions than the reference extension.

preoperative CT scans and the size of the available access window. Consideration could also be given to which approach provides more direct access to the exact location of the lesion. In certain cases, both approaches could be used in combination to increase the surgical freedom and facilitate the visualization of the surgical site by guiding the endoscope along one approach and the surgical instrument along the other. Given that both approaches use the endoscope for the most delicate parts of dissection, a similar position of the patient can be advised.

Certain limitations need to be considered when interpreting our results. First, we manually aligned the view on the 3D surface model with the endoscope view and manually marked the landmarks and points along structures. We aimed to minimize subjective errors through 2 independent raters and report the interrater error. Second, the translation from the data gained in 3D surface models to actual anatomic cases has to be confirmed in further dissections. In a real case, the structures cannot be completely skeletonized for safety reasons. However, in a recent study, the exposure of IAC was only marginally overestimated based on measurements in CT slices compared with dissections in cadavers.[25] Advances in 3D model generation and surgical planning may in addition reduce the error and increase the safety of the approaches.[33]

Our results were mainly obtained with traditional instruments for lateral skull base surgery. However, the feasibility and the surgical outcome of both approaches depend on advancements in endoscope technology and new angled instruments to expose and access the IAC from below. This factor is also reflected in the 2 studies that report successful cases with the retrolabyrinthine approach. Tan et al.[18] used a 70° endoscope and a self-designed angled suction curette to resect the tumors from the IAC. Iacoangeli et al.[21] resected the intrameatal tumors under endoscopic guidance and with "properly angled instruments." Our results on the extensions of the surgical access window and cumulative distribution thereof not only inform the discussion regarding the indications for the approaches and their feasibility but can also serve as a basis for possible developments regarding required surgical instrumentation.

CONCLUSIONS

This study examined the feasibility of 2 controversially discussed surgical approaches to the IAC, the transcanal infracochlear and the transmastoid retrolabyrinthine approach, by means of 3D surface models. The data show that approximately 80% of the measured cohort have access window extensions $\geq$3 mm for both approaches, which marked the minimal required extension in an earlier study[23] and indicates the feasibility of both approaches in a large population. In the future, with dedicated instruments, the transcanal infracochlear and the transmastoid retrolabyrinthine approach might be considered as minimally invasive alternatives to corridors to the IAC.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Tobias Butzer: Conceptualization, Methodology, Writing – original draft, Visualization, Formal analysis. **Eirik Juelke:** Conceptualization, Methodology, Writing – original draft. **Abraam Yacoub:**

Investigation, Conceptualization. **Wilhelm Wimmer:** Formal analysis, Validation. **Marco Caversaccio:** Resources, Supervision. **Lukas Anschuetz:** Writing — original draft, Supervision, Resources, Project administration, Funding acquisition.

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